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How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison

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ABSTRACT

Plug-In electric vehicles (PEV) are in an early market phase in almost all markets. Still, the lack of public charging infrastructure is a barrier to PEV adoption. The assessment of future charging infrastructure needs is often based on key figures, mainly the ratio of PEV to public charging points. However, countries differ regarding their framework conditions, e.g. the availability of home charging, and the question of how much public charging infrastructure is needed cannot be answered equally for all countries. Yet, studies analyzing the framework conditions for the medium- to long-term demand for charging infrastructure are rare. Here, we review the existing literature and summarize the evidence for the importance of framework conditions on charging infrastructure needs. Furthermore, we illustrate the literature evidence by comparing the framework conditions for charging infrastructure in different countries based on a comprehensive dataset of framework parameters. We find public charging infrastructure as alternative to home charging is only needed in some densely populated areas. However, framework conditions vary largely among countries. Accordingly, findings from literature for specific countries can only be transferred to other countries to a limited extent.

1. Introduction

Plug-in electric vehicles (PEV), both battery electric (BEV) and plug-in hybrid electric vehicles (PHEV), if powered with renewable energy, are an important instrument to cope with ambitious greenhouse gas mitigation targets (Davis et al., 2018; Plötz et al., 2017; Jochem et al., 2015). To support the diffusion of these vehicles, political actors are often confronted with the planning and rollout of public charging infrastructure (D'Appolonia et al., 2016; Harrison and Thiel, 2017). Yet, the question of how much public charging infrastructure is needed cannot be easily answered equally across countries. First, a regular charging option, such as home or workplace charging, is found to be important for the success of PEV in the early market phase (Hardman et al., 2018). While countries with a high availability of garages can rely on private charging infrastructure for regular daily charging, there is a need for (public) charging infrastructure in countries with a low garage availability (see e.g. Helmus et al., 2018 for the Netherlands). Second, public charging infrastructure with high power is necessary along travel corridors to enable long distance driving (Figenbaum and Kolbenstvedt, 2016; Nicholas and Hall, 2018). This kind of fast charging infrastructure is needed complementary to the regular charging option and depends, among others, on the frequency and length of long-distance trips (Nicholas and Hall, 2018; Gnann et al., 2018).

In a recent review, Hardman et al. (2018) show that 50–80% of all charging events occur at home. The second most important

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charging location is at work, where 15–25% of BEV commuters charge and slightly less for PHEV (Hardman et al., 2018). Less than 10% of all charging events occur at the remaining locations: public slow charging locations and fast charging along long-distance travel corridors (Hardman et al., 2018).

1.1. Scope of this study

Previous analyses of the international context of charging infrastructure point out the importance of country-specific requirements on charging infrastructure. However, while some country specific differences, such as different ratios of electricity to fuel cost (c.f. Nicholas and Hall, 2018), are mentioned as important influencing factors for PEV adoption, a systematic and quantitative country-by-country comparison of charging infrastructure framework conditions is missing in literature. Thus, the aim of this study is twofold: First, we review the literature to identify empirical regularities on charging infrastructure needs that are stable across studies. We summarize these empirical regularities as "stylized facts". Second, for every stylized fact, we define a set of important factors or parameters, respectively (Section 3.2). These factors are then analyzed for different countries in the second part of the paper (Section 4). Due to the early PEV market stage in all countries but Norway, the second part of the paper does not contain a statistical analysis, but it is intended to illustrate the current and future importance of the framework conditions in different countries. Accordingly, our study can serve as basis for decision-making on how infrastructure can meet country-specific requirements for a successful market diffusion of PEV beyond the early market.

In our analysis, we differentiate between charging infrastructure demand and needs. *Demand* for charging infrastructure is indicated from empirical charging behavior (c.f. Tal et al., 2018). Charging infrastructure *needs* in contrast are estimated, based on the required number of charging points deemed necessary to fulfill today's travel need by car (Gnann et al., 2018a). Accordingly, charging demand might exceed the charging infrastructure needs due to the influence of range anxiety, comfort, bounded rationality, or other aspects. Another factor that might determine the deployment of charging infrastructure is a so called optional value of charging infrastructure. Carley et al. (2019) find that the perception of charging availability and seeing chargers has a positive effect on the intent to purchase or lease BEV. Globisch et al. (2019) also find that public charging infrastructure may be important to attract other groups than the classical early adopters of PEVs. Since our country-by-country comparison is mainly based on techno-economic parameters (see Section 2), we focus on charging infrastructure needs and exclude charging infrastructure demand from our analysis.

Public charging infrastructure is publicly accessible and is located on land owned by the public. Here we assume that a charging point is publicly accessible "if it is located either in public street space or on private land, if it can actually be entered and used by an unspecified group of people" (BMWi, 2015). We analyze three types of public charging infrastructure for light duty vehicles: (1) charging (near home) as a substitute for private charging, (2) opportunity charging while parking at points of interest (POI charging), e.g., at grocery stores, and (3) fast charging, mainly along travel corridors with high charging power, to enable long-distance travel (DC high power charging). Our analysis focuses on the US, Europe, China and Japan since these markets comprise more than 97% of the global PEV market (IEA, 2018). In Europe, we focus on Norway, as the most important PEV market, France, Sweden, UK, the Netherlands and Germany as important car markets and on Poland as representative of an early Eastern European PEV market. In some cases, we take a closer look at the States of California, New York, Texas, and Vermont in the US. Since California comprises almost half of all new PEV registrations in the US (DOE, 2018a; veloz, 2019), it is important for our analysis not to just look at the US average. New York is an early adopter state as well. Texas is included due to its market size and Vermont for a smaller state that has the potential for early PEV adoption.

2. Methods

We first review existing literature to identify framework conditions that influence public charging infrastructure needs and retrieve stylized facts from these studies. We define those framework conditions as country-specific factors that might lead to different charging infrastructure needs, such as the share of long-distance trips or charging infrastructure density. Using search terms related to electric vehicle charging infrastructure (requirements, demand, needs, influence on electric vehicle sales), we identify literature eligible for our analysis based on titles. We exclude irrelevant studies from our analysis based on their abstracts, e.g., studies optimizing charging infrastructure rollout for specific urban areas. Please be aware that this review style is more of a narrative nature and not comprehensive. We screen the studies identified as relevant to extract and summarize their key findings (see Table 1). These findings are condensed to four stylized facts (SF). These stylized facts represent findings that are valid across studies and thus summarize the present state of knowledge on important framework conditions of charging infrastructure needs.

Based on these findings, a set of parameters is identified as characteristic for the different stylized facts in the second part of the paper (Section 4). Only parameters that are relevant to determine charging infrastructure needs in terms of number of charging points are considered. These parameters are then studied and compared for different countries. In addition, the status quo of charging infrastructure deployment in the different countries is analyzed as a basis for comparison. Finally, we discuss our findings based on selected country-specific narratives.

The structure of our approach consists of four main parts:

1. Literature review on charging infrastructure needs and retrieval of stylized facts (Section 3.1)
2. Operationalization of stylized facts with parameters (Section 3.2)
3. Parameter data collection and cross-country analysis of stylized facts (Section 4)
4. Country-specific recommendations based on findings and proposal of fields for further research (Section 4.6)

Table 1
Reviewed studies on charging infrastructure requirements by country.

Author	Year	Title	Country	Estimated techno-economic demand	Charging infrastructure demand due to psychological or other reasons	Empirical charging infrastructure usage	Key Findings
Baresch, Moser	2019	Allocation of e-car charging: Assessing the utilization of charging infrastructures by location.	Austria	x	x		88% of charging events at home and 8.8% at work. Public charging both fast and slow with minor share.
Dong et al.	2014	Charging infrastructure planning for promoting battery electric vehicles: an activity-based approach using multiday travel data.	USA	x			Public charging infrastructure reduces range-constrained days and trips. Fast chargers along travel corridors are essential for BEV long distance travel.
Dunckley, Tal	2016	Plug-In Electric Vehicle Multi-State Market and Charging Survey	USA			x	Most users charge mainly at home. 57% of users charge only at home, 40% use home, workplace and public charging. Charging away from home is mainly work related. Only 32% commute and charge at work or near work. The number of users that used any type of public charging is small and few of these had used DC fast charging.
Figenbaum, Kolbenstvedt	2016	Learning from Norwegian Battery Electric and Plug-in Hybrid Vehicle Users.	Norway			x	For long distance travel, fast charging is used most. Almost all owners charge their vehicle at home. Charging at work is relatively common for BEV. Public normal charging is not frequently used.
Figenbaum	2019	Charging into the future - Analysis of fast charger usage	Norway			x	Various recommendations are drawn from the analysis. Among others, the author points out the importance to understand the high variability of fast charging needs in different situations and regions.
Funke, Plötz	2017	A techno-economic analysis of fast charging needs in Germany for different ranges of BEV	Germany	x			For private cars, charging infrastructure needs decrease for higher vehicle ranges. Charging infrastructure needs are dominated by geographic coverage for a BEV stock smaller 50.000 vehicles.
Gnann et al.	2018a	Fast charging infrastructure for electric vehicles: Today's situation and future needs	Sweden, Norway, Germany	x			We do not need much fast charging infrastructure to satisfy user demand.
Gnann et al.	2018b	What drives the market for plug-in electric vehicles? A review of international PEV market diffusion models	Worldwide	x			Use of public charging stations is likely to depend on the availability of other charging options (home and workplace).
Gnann et al.	2018c	Can public slow charging accelerate plug-in electric vehicle sales? A simulation of charging infrastructure usage and its impact on plug-in electric vehicle sales for Germany	Germany	x			Public slow charging does not support the market diffusion of plug-in electric vehicles in Germany, private and workplace charging is more important.
Gnann, Plötz, Wietschel	2015	How to address the chicken-egg problem of electric vehicles? Introducing an interaction market diffusion model for EVs and charging infrastructure	Germany	x	(x)		Home charging is most important. The second best option is charging at work, which is affordable for a large number of users as well. Thus, a second charging point at work increases the number of private PEV owners also when its payment is considered.

(*continued on next page*)

Table 1 (*continued*)

Author	Year	Title	Country	Estimated techno-economic demand	Charging infrastructure demand due to psychological or other reasons	Empirical charging infrastructure usage	Key Findings
Graham-Rowe et al.	2012	Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations	UK		x		Advanced vehicle technology and charging infrastructure are important for mainstream drivers to consider buying a PEV.
Hall, Lutsey	2017	Emerging best practices for electric vehicle charging infrastructure	Worldwide	(x)			Regression analyses suggest that both Level 2 and DC fast charging play a role for electric vehicle drivers.
Hardman et al.	2018	A review of consumer preferences of and interactions with electric vehicle charging infrastructure	USA, Canada and European countries	x		x	The development of charging infrastructure should be a part of a more general policy of promoting electric vehicles. Home charging most important for encouraging PEV purchase. On average, 50–80% of charging events for BEV and PHEV at home. In China and the Netherlands, most consumers do not have home charging access. Public charging stations are used less frequently, but are important for long journeys (safety of charging).
Harrison, Thiel	2017	An exploratory policy analysis of electric vehicle sales competition and sensitivity to infrastructure in Europe	Norway	x			Charging infrastructure is important to enable market uptake beyond typical early adopters (PEV stock above 5%). Extensive public charging availability (more than 1 charging point per 10 PEV) with little gains but high costs.
Helmus et al.	2018	Assessment of public charging infrastructure push and pull rollout strategies: The case of the Netherlands	Nether-lands			x	Public charging as substitute for home charging. Demand driven charging infrastructure appear in higher-density areas (more users with no home charging). At this charging infrastructure, charging happens overnight, 50% charging time/parking time. Higher charging power not necessary. In a less mature market, demand driven charging infrastructure is necessary.
Levinson, West	2018	Impact of public electric vehicle charging infrastructure	US	x			DC fast charging has higher impact on PEV sales than public slow charging.
Liu	2012	Electric vehicle charging infrastructure assignment and power grid impacts assessment in Beijing	China	x			Charging at home with major role, but the availability of parking spaces restricts the ability to both home and work charging. Therefore, demand is shifted to fast charging. Fast charging should be more distributed along the highways for long-distance journeys.
Morissey et al.	2016	Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour	Ireland			x	Electric vehicle users preferably charge at home in the evening at peak demand times. Fast chargers are mainly at petrol stations. Charging infrastructure at other locations such as on-street parking might be required, but the usage frequencies appear low. Thus, they mainly

(*continued on next page*)

Table 1 (*continued*)

Author	Year	Title	Country	Estimated techno-economic demand	Charging infrastructure demand due to psychological or other reasons	Empirical charging infrastructure usage	Key Findings
							might serve to both providing visibility for potential customers and also lead to lower range-anxiety of existing users.
Nazari et al.	2019	Modeling electric vehicle adoption considering a latent travel pattern construct and charging infrastructure.	California		x		In a revealed preference model public charging infrastructure only important for households choosing PHEV and insignificant for BEV utility.
Neaimeh et al.	2017	Analysing the usage and evidencing the importance of fast chargers for the adoption of battery electric vehicles	UK, US			x	Fast charging more influential than slow charging. Fast charging helps overcome perceived range barriers. There is a need for political support to extend fast charging infrastructure.
Nicholas et al.	2011	DC fast as the only public charging option? Scenario testing from GPS tracked vehicles	California	x			Public fast charging infrastructure is used for rare long distance trips.
Nicholas et al.	2017	Advanced Plug-in Electric Vehicle Travel and Charging Behavior.	USA			x	The likelihood of charging in public is a function of range recovered, not vehicle range.
Philipsen et al.	2016	Fast charging station here, please! User criteria for electric vehicle fast-charging locations	Germany		x		Motorway service stations, shopping facilities, and traditional fuel stations are potential fast-charging station locations.
Reuter-Oppermann et al.	2017	How many fast charging stations do we need along the German highway network?	Germany	x			Especially in the beginning market diffusion of BEV, an optimal allocation of (fewer) fast charging EVSE will increase their profitability significantly.
Sierzchula et al.	2014	The influence of financial incentives and other socio-economic factors on electric vehicle adoption	Worldwide		x		Financial incentives, charging infrastructure, and local production facilities are found to be significant and positively correlated to a country's electric vehicle market share. Charging infrastructure most strongly related to electric vehicle adoption. However, neither financial incentives nor charging infrastructure ensure high electric vehicle adoption.
Skippon, Garwood	2011	Responses to battery electric vehicles: UK consumer attitudes and attributions of symbolic meaning following direct experience to reduce psychological distance.	UK		x		Home charging is most important. Public charging infrastructure potentially important to foster PEV diffusion.

3. Literature review

3.1. Analysis of charging infrastructure needs

The following literature review aims at identifying important parameters that represent influencing factors for charging infrastructure needs that might differ by country. Thus, the following 26 studies reviewed describe or model charging infrastructure needs from a technical, economic or psychological point of view. They include PEV market diffusion models, charging surveys, analyses on current charging infrastructure usage as well as studies analyzing the impact of charging infrastructure availability on PEV diffusion. Our literature review does not aim at giving an exhaustive overview of literature on charging infrastructure but focuses on the aim of deducing stylized facts and a parameter set that describes important framework conditions for charging infrastructure needs. The studies considered in this review are described in Table 1 and their most important findings are summarized in this section.

Although both the importance of charging infrastructure for PEV adoption and the question of how much charging infrastructure is needed has gained broad attention in literature, only a limited number of studies analyzed charging infrastructure requirements in a broader international context. Broadbent et al. (2017) analyze policy (best) practices to foster PEV adoption in Europe and the US. They find that an implementation of multiple measures is necessary to foster PEV diffusion rather than focusing on any single measure. The authors underline the financial effectiveness of subsidizing public charging infrastructure compared to direct PEV purchase incentives and the importance of a well-functioning and appropriately distributed charging infrastructure network on PEV uptake. However, the broad perspective of the study does not allow for a detailed analysis of charging infrastructure needs, especially varying requirements in different countries. Hall and Lutsey (2017) analyze best practices of public charging infrastructure in major PEV markets globally. The authors perform regression analyses and acknowledge that the need for public charging infrastructure is not equal between metropolitan areas. In their analysis, the authors identify the availability of private charging infrastructure to be an important factor for charging infrastructure needs. The conclusions of the authors are based on current charging infrastructure requirements. Nicholas and Hall (2018) find that public charging infrastructure needs vary from region to region. The authors further highlight that fast charging needs depend on PEV market development, access to other charging types and driving patterns. The study especially highlights the higher need for fast charging if it is not only deployed for long distance driving, but also used regularly by PEV drivers with few charging options. The authors conclude that there is a business case for fast charging infrastructure, which in turn depends on local differences such as the ratio of fuel to electricity cost. The study provides a broad overview on influencing factors of charging infrastructure, focused exclusively on fast charging.

Hardman et al. (2018) reviewed 58 studies on charging infrastructure location, access, payment, charging cost, charging management, and charging infrastructure needs with focus on the consumer perspective. The authors provide an extensive overview of current charging behavior and general charging infrastructure requirements. The authors find home charging among early adopters to be most important but postulate a need for further research on determining charging infrastructure needs, especially for upcoming higher battery ranges. The authors focus on an extensive literature review, accordingly, a quantitative comparison of different countries is beyond the scope of their study.

The effect of charging infrastructure on PEV sales has been studied in a number of papers based on empirical data with different forms of econometric analysis or simulation. Sierzchula et al. (2014) perform regressions on national vehicle sales for 30 countries and find charging infrastructure, together with financial incentives and the presence of local facilities, to be significant and positively correlated with PEV market shares. Plötz et al. (2016) analyze European countries and US states and find a positive and significant effect on sales. Even at municipal and regional level, Mersky et al. (2016) find a positive correlation in Norway and Wang et al. (2017) similarly in China. Clinton and Seinberg (2019) apply panel data regression with time and state fixed effects to quarterly US state-level data for 2010–2014. They find a significant correlation with BEV sales, but note that the effect appears to be smaller than for financial incentives. Narassimhan and Johnson (2018) investigate the effect of charging infrastructure deployment on sales more specifically for the US and find that the correlation of public charging and vehicle purchases per capita increases with the electric driving range of a PHEV, while it decreases with rising BEV range (due to lower range anxiety with higher range). The positive correlation alone does not indicate the direction of causality between charging infrastructure and PEV sales. Yet, the establishment of charging stations does not follow a market logic yet and is rather driven by subsidies and regulations (Serradilla et al., 2017; Jochem et al., 2016; European Parliament, 2014). Accordingly, public charging infrastructure is not built due to more PEV, but PEV sales increase due to more public charging infrastructure.

There are studies that either do not report the direction of the effect or find inconclusive relationship (Jin et al., 2014; Slowik and Lutsey, 2017; Hall and Lutsey, 2017). Li et al. (2017) study the indirect network effects between PEV sales and deployment of charging infrastructure. They find that subsidizing charging infrastructure would result in larger PEV adoption compared to sales incentives. While the various studies take different country-specific factors related to PEV sales into account, none of them explicitly considers country specific framework conditions concerning charging infrastructure such as garage availability.

Different charging infrastructure requirements have a high influence on the type of charging infrastructure needed in different countries as found by Gnann et al. (2018b) who analyze 40 market diffusion models from 16 different countries. In Germany for example, private parking, e.g. in garages or dedicated parking spaces, is widely available (c.f. Infas et al., 2018). Consequently, private (overnight) charging infrastructure can be installed at low cost, whereas public charging infrastructure with low charging power (< 22 kW) hardly has an influence on PEV diffusion in Germany (Gnann et al., 2018c; Gnann, 2015). In contrast, in the Netherlands, the availability of private (overnight) charging infrastructure is low and public slow charging infrastructure is needed as a substitute. Helmus et al. (2018) find that public "demand-driven" charging infrastructure is mainly used for overnight charging and "strategic" charging infrastructure, mainly placed at points of interest (POI), is rather used for opportunity charging while parking

Table 2
Stylized facts (SF) and influencing factors of charging infrastructure requirements as well as confirming studies.

No.	Stylized facts (SF)	Influencing factors/Parameters	Citation	Country
SF1	The availability of charging infrastructure supports PEV diffusion.	Existing charging infrastructure	Skippon and Garwood (2011)	UK
		PEV stock (BEV, PHEV)	Graham-Rowe et al. (2012)	UK
		New registrations per year PEV sales share	Figenbaum and Kolbenstvedt (2016)	Norway
		GDP per capita	Harrison and Thiel (2017)	Norway
		Vehicle per capita	Levinson and West (2018)	USA
			Sierzchula et al. (2014)	World
SF 2	Broad availability of home charging infrastructure is sufficient for the early market diffusion of PEV.	Share of detached houses Share of urban population/	Hardman et al. (2018)	Mainly USA, Canada and European countries
		Population density	Gnann et al. (2018b)	Worldwide
		Share of home charging	Figenbaum and Kolbenstvedt (2016)	Norway
			Gnann et al. (2015)	Germany
			Morissey et al. (2016)	Ireland
			Skippon and Garwood (2011)	UK
			Dunckley and Tal (2016)	USA
			Neaimeh et al. (2017)	UK
			Baresch and Moser (2019)	Austria
SF 3	Public slow charging infrastructure is only needed as a substitute for home charging (SF3), since charging at points of interest (POI) has a limited effect on the diffusion of PEV.	SF 1 and SF 2	Nicholas et al. (2012)	California
			Nicholas and Tal (2017)	USA
			Hall and Lutsey (2017)	World
			Figenbaum and Kolbenstvedt (2016)	Norway
			Morissey et al. (2016)	Ireland
			Helmus et al. (2018)	Netherlands
			Gnann et al. (2018c)	Germany
			Liu (2012)	China
			Nazari et al (2019)	California
SF4	DC high power charging infrastructure is mainly needed for BEV long-distance trips.	Share of DC charging infrastructure	Funke and Plötz (2017)	Germany
		Share of BEV	Morissey et al. (2016)	Ireland
		Share of long distance trips (driving behavior)	Dong et al. (2014)	USA
		Country size	Figenbaum and Kolbenstvedt (2016)	Norway
		Highway network: length and coverage	Nicholas and Tal (2017)	USA
			Reuter-Oppermann et al. (2017)	Germany
		Charging power	Liu (2012)	China
			Hardman et al. (2018)	Mainly USA, Canada and European countries
			Gnann et al. (2018a)	Sweden, Norway, Germany
			Philipsen et al. (2016)	Germany

during daytime.

In the US, the UK and Norway, drivers are found to drive their BEV more if high power charging is available (Axsen and Kurani, 2013; Neaimeh et al., 2017; Figenbaum and Kolbenstvedt, 2016). The comparably high amount of energy that is transferred during one fast charging stop, indicates that charging might be needed for long distance driving in contrast to the use of POI charging as a "top-up" (Morissey et al., 2016; Neaimeh et al., 2017; Figenbaum, 2019). While these findings base on empirical findings at fast chargers with mostly up to 50 kW and 120 kW for Teslas, respectively, fast charging will become even more convenient in the near future due to efforts to increase charging power. Currently, fast charging infrastructure with high power up to 350 kW is or will be installed mainly at highway corridors, often at existing gasoline stations (for Ireland, UK, the US, Germany, the Tesla Supercharger network, see e.g. Morissey et al., 2016; Neaimeh et al., 2017; Electrify America, 2018; Figenbaum, 2019). In Germany, for example, already 5% of fast chargers have up to 350 kW charging power in 03/2019 (BNetzA, 2019).

The broad scope of the studies analyzed allows us to deduce empirical regularities or stylized facts on the influencing factors of charging infrastructure needs despite some limitations of the different approaches (see Table 2). While studies modeling charging behavior (see column "Estimated techno-economic demand" in Table 1) often rely on data from conventional vehicles and thus a direct transferability to PEV charging behavior is uncertain, their modeling approaches can identify and assess various influencing factors. On the other hand, empirical analyses on PEV market uptake (see "Empirical charging infrastructure usage" in Table 1), PEV driving, PEV charging, or PEV user experience refer to early adopters of the still limited PEV market (< 3% PEV market share in most countries, IEA, 2018). Nevertheless, especially the fast market uptake of PEV in Norway allows for interesting insights, especially when comparing empirical charging infrastructure demand and charging infrastructure needs as estimated from PEV modeling in the studies mentioned before.

3.2. *Stylized facts and connected measures*

We summarize our findings from the literature in four stylized facts (SF) as shown in Table 2. For each stylized fact, we deduce a parameter set that illustrates important factors for charging infrastructure needs.

SF1: The availability of charging infrastructure supports PEV diffusion. The diffusion of PEV varies between markets, which leads to different charging infrastructure needs for different countries or states now. Public charging infrastructure can increase PEV sales but the effect appears to be minor.

The parameter set contains the parameters *PEV market shares* (registrations and stock), number of *PEV registrations per capita, BEV sales share* and the vehicle-to-refueling-station index (*VRI*, see Yeh, 2007), that is the ratio of PEV per charging points. For the VRI, we differentiate by PEV and charger type (slow/AC or fast/DC). In addition, we use the relative parameter *charging sites per gasoline station* (c.f. Levinson and West, 2018).

SF2: Broad availability of home charging infrastructure is sufficient for the early market diffusion of PEV. We analyze this aspect by comparing the following parameters as an indicator of home charging availability: *share of (semi-) detached houses*, *share of urban population* and, if available, the *share of home charging* (as share of all charging events) of current PEV. In addition, we analyze average *annual driving distances* to analyze comfortability and suitability of home charging for average daily driving distances.

SF3: Public slow charging infrastructure is only needed as a substitute for home charging, since charging at points of interest (POI) has a limited effect on the diffusion of PEV. We will discuss this stylized fact by relating parameters for home charging availability to the current status of public charging infrastructure diffusion, since public slow charging infrastructure needs are dependent on the availability of other charging options, mainly home charging (cf. Gnann, 2015; Helmus et al., 2018).

SF4: DC high power charging (HPC) infrastructure is mainly needed for BEV long-distance trips. As an indicator of the (current) importance of DC fast charging, the parameters *DC fast charging coverage* (km^2 per site, highway-km per site) and the *share of public fast charging* are compared. In addition, we explicitly analyze the *share of long-distance trips* as well as *highway network coverage* that might indicate charging infrastructure needs for geographical coverage.

Finally, early adopters of PEV in various countries are often found to have an income above average and to live in suburban areas (Plötz et al., 2014; Campbell et al., 2012; Radtke et al., 2012). In addition, car ownership and use differ by country which influences PEV market diffusion and charging infrastructure needs, respectively. Accordingly, we start our country comparison with general statistics, such as *GDP per capita, the Gini index,* the *motorization rate* (vehicle per capita), and the *share of urban population.*

4. International comparison of framework conditions for charging infrastructure

We now compare the above-mentioned parameters for different countries to illustrate the stylized facts (SF). The following paragraphs are structured according to the stylized facts identified in the literature review. We first start with a general comparison of the different countries to highlight that they start from different positions with regard to economic and technical adoption of electric vehicles. We then provide the status quo of infrastructure construction (SF 1) and building upon this, we discuss the framework conditions for private and public charging infrastructure (SF 2 and SF 3). Finally, we analyze fast charging needs (SF 4) within the different countries.

If not stated otherwise, our data refers to 2017 since it contains the most recent and reliable data with regard to a data basis that is as uniform as possible - as for example the IEA's Global EV Outlook (IEA, 2018).

4.1. General conditions

In this paragraph, we provide some background information on the different countries regarding their economic conditions, their settlement structure, and their total passenger car market since these affect PEV market success and thus directly influence charging infrastructure needs.

The countries under consideration differ notably with regard to their economic power, but with a core of countries with comparable purchase potential (IMF, 2017, cf. Table A1 in the supplement). The core of these countries comprises the Western European countries and Japan with an average gross domestic product (GDP) per capita ranging between 40,000 and 50,000 USD (based on purchasing power parity). In contrast, China has the lowest GDP per capita in our dataset with ~17,000 USD, while Norway has the highest with ~71,000 USD. The US GDP of ~59,000 USD per capita is the second highest. The analyzed US states also differ notably. While the GDP of Texas and Vermont are comparable to the US average, California (~74,000 USD) and New York (~86,000 USD) have a considerably higher GDP.

Income is least evenly distributed in the US and China as indicated by the high Gini indices of 41.5 and 38.6 (World Bank, 2017, see Table A1). Particularly in China, the uneven income distribution compensates for a low average income in terms of purchasing power potential, which is necessary for the introduction of PEV in the early market phase. In contrast, Norway is the country with the most evenly distributed income (Gini index below 28). The high GDP of Norway and the low inequality in income distribution (low Gini index) underline the importance of the country's wealth for the market success of electric vehicles, in the sense that it has been important for its long history of subsidies for PEV (for the subsidies c.f. Figenbaum, 2017). However, for the other countries, the aspect of economic power should be of secondary importance, since on the one hand, most of the countries have a comparable GDP per capita and on the other hand, the unequal distribution of wealth in China might allow for a high share of potential PEV early adopters despite its comparably low average GDP.

The role of cars in everyday life differs strongly among the countries, as indicated by the motorization rate and the share of passenger-km (pkm) performed by car (see Table 3). In European and North American countries, the share of pkm by car ranges from 77 to 90%, consistent with high rates of motorization between 477 and 811 light vehicles per 1000 inhabitants. In both metrics, the US have the highest car dependency. Japan has a comparatively high modal share for rail transport leading to 65% of pkm by car whereas car ownership is comparable to Western Europe with 615 cars per 1000 inhabitants. Both car ownership and modal share of car are still low in China but have significantly increased over the past decade.

The passenger car stock turnover rate, i.e. the ratio of yearly new registrations to total passenger car stock, is an important indicator of how quickly the transfer of the passenger car stock from conventional vehicles to plug-in electric vehicles can take place (in combination with PEV sales shares). In most of the countries, the turnover rate ranges from five to ten percent (see Table A1 in the supplement), while the fast growth of the vehicle market in China is mirrored in a high turnover rate above ten percent. In Poland, the turnover rate is just above two percent, indicating that a complete electric car stock could take about 50 years if this was not subject to change which is a rather challenging circumstance for the success of alternative fuel vehicles such as PEV.

For public charging infrastructure, the share of urban population as well as population density represent important indicators for potential PEV usage and charging needs. With about 80 to 90%, the share of urban population is in a comparable range for most of the countries. However, in China and Poland the urban share is the lowest with 60%. The population density is particularly high in Chinese megacities: While average population density in China is ~150 people per km^2, it amounts to 500 people per km^2 on average in the metropolitan area of Beijing and to more than 2000 people per km^2 in Shanghai – with much higher density in the urban districts of these cities (WPR, 2019). In contrast, the Netherlands has a high urban population share of 92% and the highest population density at national level (~420 per km^2). This is an important background information for the potential availability of home charging (SF2). All mentioned parameters are summarized in Table A1 in the supplement.

4.2. SF1: The availability of charging infrastructure supports PEV diffusion.

As stated above, the positive correlation between charging infrastructure availability and PEV diffusion is broadly documented in the literature and PEV sales increase with public charging infrastructure (see Section 3.1). Thus, we limit ourselves to presenting the 2017 status quo of PEV market and charging infrastructure availability in the different countries. However, please note, that the effect of public charging availability on PEV diffusion is limited. More specifically, financial incentives are more important for PEV diffusion than public charging infrastructure (Clinton and Steinberg, 2019; Jenn et al., 2018). In addition, charging infrastructure need as perceived by PEV users might depend on range anxiety. For example, Narassimhan and Johnson (2018) find a decreasing correlation between public charging infrastructure availability and PEV sales for longer range BEV. In that sense, the following discussion is to serve as illustration of the role of public charging infrastructure in the different countries.

There are noteworthy differences regarding the status of PEV market diffusion worldwide. Norway has the highest PEV sales

Table 3
Modal share of cars in pkm and motorization in selected countries (Sources: EC, 2018; ITF, 2019; Sugiyama, 2015).

Parameter	China	US	France	Germany	Japan	Nether-lands	Norway	Poland	Sweden	UK
Share of pkm performed by car [%]	45	90	80	84	65	86	88	77	82	85
Light vehicles per 1000 inhabitants	179	811	479	555	615	481	506	571	477	484

Table 4
PEV market data (year 2017). Data sources: IEA (2018), eafo (2017), UN (2017), Fraunhofer ISI (2017).

Parameter	China	US	France	Germany	Japan	Netherlands	Norway	Poland	Sweden	UK	World
PEV sales share 2017 [%]	2	1	2	2	1	3	39	0.2	6	2	
Share of BEV in PEV sales [%]	77	53	78	54	51	18	66	52	25	34	62
PEV registrations per 1000 inhabitants	0.9	2.3	1.8	1.3	1.6	6.9	33.9	< 0.1	5.1	2.1	0.4
CAGR (2013–2017); stock [%]	148	45	58	73	31	43	83	102	31	95	69
Average BEV battery capacity (sales weighted 2015–2017) [kWh]	32	58	33	38	32	55	42	41	48	37	39

shares worldwide whereas China is the largest PEV market in terms of absolute sales (IEA, 2018). Furthermore, the share of BEV and PHEV in sales (and stock) also varies considerably between countries. In addition to country-specific general framework conditions, this share is also strongly dependent on local incentives. With a PEV sales share of 39% in 2017 (see Table 4) and 46% in 2018 (IEA, 2019), market diffusion of PEV is by far highest in Norway, followed, with large distance, by Iceland with 12% (not shown in the table, IEA, 2018) and Sweden with 6%. In Poland, only 0.2% of vehicles sold were PEV. The other countries have PEV sales shares ranging from 1 to 2%. Within the US, California is the most important PEV market. In 2017, 5% of vehicles sold were PEV. In contrast, in Texas this number was only 0.4%. New York (1%) and Vermont (2%) are in the middle range.

The share of BEV compared to PHEV in sales varies among countries and over time. For example, the Netherlands had high incentives for PHEV leading to strong sales' increase during 2013–2016 (with a peak of 9% PHEV sales share and 1% BEV sales shares in 2015). The sales of PHEV in the Netherlands decreased dramatically due to a change in incentives started at the end of 2016.

As indicated by the compound annual growth rate (CAGR) between 2013 and 2017, the PEV market has grown quickly in all countries, especially in China (please refer to the Appendix – Table A2 – for more details, and especially on single US States).

Finally, the average sales weighted BEV range differs largely by country (Table 4, own analyses based on Fraunhofer ISI (2017) and Thielmann et al. (2018)). While battery capacity in China and Japan was lowest with 32 kWh on average between 2015 and 2017, closely followed by France with 33 kWh, it was nearly twice as high in the Netherlands (55 kWh) and the US (58 kWh). The different battery capacities are due to different models dominating the national car markets, often by domestic car brands. In China various domestic car makes dominate sales, in France the Renault Zoe dominates sales and the Japanese BEV market consists almost exclusively of Nissan Leaf. Due to the rather limited battery capacity of these models (from 2015 to 2017), average battery capacities in these countries are rather low. In contrast, in the US, Tesla makes up a large part of the BEV market, leading to high average battery capacities.

In half of the countries, average battery capacities of BEV sold in 2017 were almost identical than for the time period 2015–2017, while in the other countries battery capacities increased. In France, sales weighted battery capacities for 2017 were 37 kWh (compared to 33 kWh in 2015–2017), in Japan 40 kWh (compared to 32 kWh), in Norway 46 kWh (compared to 42 kWh), in the UK they increased notably to 47 kWh (compared to 37 kWh) and finally in the US they reached 64 kWh in 2017. Since these battery capacities vary largely, they are important for the interpretation of charging infrastructure needs, due to range limitations and the related range anxiety.

The 2017 status quo of charging infrastructure availability is summarized in Table 5. According to the aim of our paper, we focus on the vehicle-to-refueling index (VRI) as relative indicator (here: PEV per charging point). A high VRI could indicate a more developed PEV market (in terms of relatively high vehicle shares in sales and stock) since the point of building a minimum charging network was passed. In contrast, a low VRI could analogously indicate either a less developed PEV market with low PEV diffusion or a high share of public AC slow charging infrastructure as alternative to home charging.

Sweden, the US and Norway have the highest VRI regarding all charging points, ranging from 12 to 19 PEV per charging point. This is in line with these markets being among the most developed ones. Additionally, in these three countries, BEV ranges are among the highest. In contrast, the lowest VRI of 4 PEV per charge point can be found in the Netherlands and Poland, indicating a comparably high availability of public charging infrastructure per PEV. While in Poland the most probable explanation might be the less developed PEV market (cf. Table 4), in the Netherlands the high share of public slow charging infrastructure is reflected by its remarkably low share of public DC fast charging infrastructure (see Fig. 1). While the share of DC charging points ranges from 10% to 15% for most of the countries, including the US states, it is as low as 1.0% in the Netherlands. In contrast, China has the highest share of about 40% DC charging points. Hence, in China, DC charging might be a substitute for missing private charging (cf. SF3), for which the smaller BEV battery capacities might be an additional indicator.

Table 5
Status quo (year 2017) of charging infrastructure availability. Data sources: IEA (2018); EAFO (2017); Eurostat (2017); AFDC (2017); R&M (2019). CP = charging point.

Parameter	China	US	France	Germany	Japan	Netherlands	Norway	Poland	Sweden	UK	World
PEV per charge point	6	17	7	5	7	4	19	4	12	10	7
BEV per DC fast charge point	11	64	59	28	14	46	94	6	20	22	17
ICEV per gasoline station	2200	1600	2900	3000	1900	2000	1400	2900	1500	3400	n/a
CP (DC + AC) per gasoline station	1.94	0.27	1.43	1.68	0.72	8.03	5.24	0.06	1.37	5.45	n/a

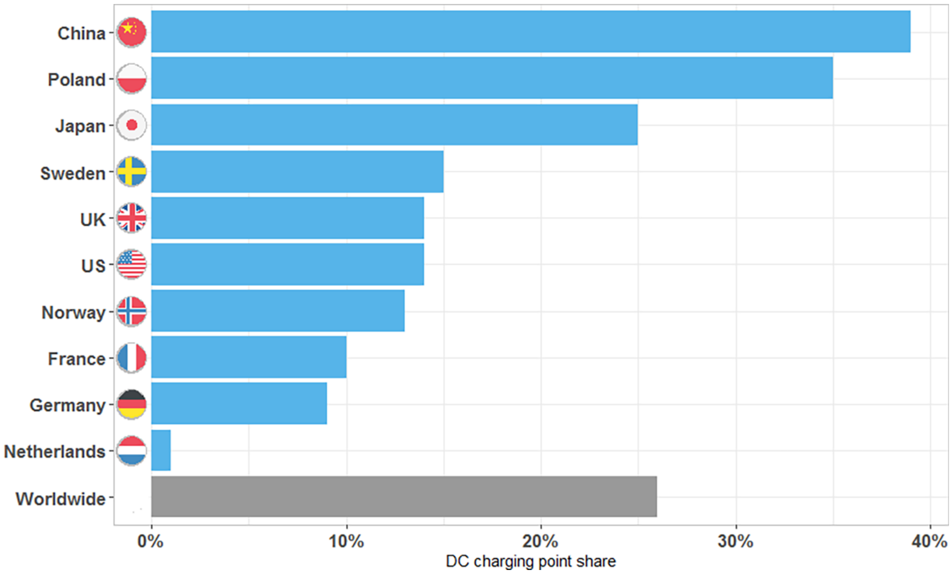

Fig. 1. Share of DC charging points among all public charging points for the different countries and globally. Data Source: IEA (2018).

As a reference, Table 5 also provides the VRI for internal combustion engine vehicles (ICEV per gasoline station). The high spread between the countries is remarkable: the VRI ranges from about 1500 ICEV per gasoline station in US, Norway, and Sweden to more than 3000 ICEV in Germany and the UK. The differences in the VRI cannot be directly explained by differences in traffic volume (for daily VKT see Table A1). However, one explanation might be that the low population density in the countries is in line with a low VRI since relatively more gasoline stations (resulting in a lower VRI) are needed for a geographical coverage (see Table A1 in the Appendix for data on population density). Please note, that here the number of gasoline stations forms the denominator whereas for PEV every single charging point is counted (where nozzles would be the equivalent). Accordingly, these numbers are not directly comparable. Yet, the ratio of public charging points to the number of gasoline stations is an indication for either advanced charging infrastructure development or for the specific need for public charging infrastructure. In countries with no or only few private charging options, the share of public charging points to gasoline stations should be higher, as it is the case for the Netherlands (cf. Table 5).

Based on these parameters, we can confirm a connection between PEV sales and charging infrastructure. Nevertheless, our results also underline the importance of different charging infrastructure types for the different countries. That is, the availability of home charging might decrease the need for public charging infrastructure, which would instead be needed for long distance driving or serving as a safety grid to reduce range anxiety. Accordingly, a detailed analysis of the different charging infrastructure types is necessary, as discussed in the following. Please note that an analysis of financial incentives is beyond the scope of this study.

4.3. SF2: Broad availability of home charging infrastructure is sufficient for the early market diffusion of PEV.

Among current PEV users, the use of private charging infrastructure at home is very important. In a review of international studies, Hardman et al. (2018) found that 50–80% of charging events happen at home. In Norway, the share is even above 90% (Figenbaum and Kolbenstvedt, 2016). Similarly, Neiameh et al. (2017) found that in the UK 72% of the energy for PEV was charged at home. Accordingly, the availability of private charging infrastructure among current PEV users is high (Figenbaum and Kolbenstvedt, 2016; Hardman et al., 2018) and the lack of home charging availability is often found to be a barrier for PEV adoption (Ajanovic and Haas, 2016; Axsen and Kurani, 2013; Figenbaum and Kolbenstvedt, 2016).

A high availability of home parking in the major PEV markets is thus an important favoring condition and the high share of home charging found among early adopters indicates that home parking should be broadly available in these countries. However, due to lack of data on home parking availability for different countries, we analyze the building share of detached and semi-detached houses as an approximation, since we expect a high probability of home charging being available at detached houses. In the US for example, the share of housing units with garage or carport (66%) is in the same magnitude as the share of detached houses (62%) (DOE, 2018b; US Census Bureau, 2017).

In all countries analyzed except for the Netherlands, the share of detached houses is above ~25%. In the US, Norway and Japan, detached houses comprise even more than half of all buildings (Fig. 2). Although the share of detached houses is not equal to the share of households having access to home parking, it nevertheless underlines the high potential availability of home parking in most of the countries, especially if taking also semi-detached houses into account. However, the availability of home charging at semi-detached houses seems unclear. While in Norway and California, the share of detached and semi-detached houses is well in line with parking availability found in literature (Figenbaum and Kolbenstvedt, 2016; Kurani et al., 2016), the comparably low availability of

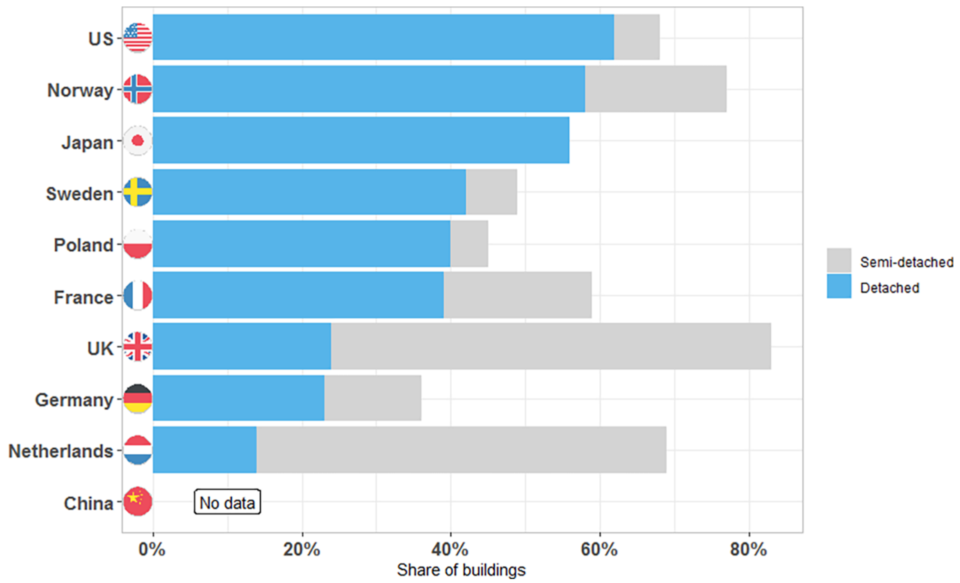

Fig. 2. Share of detached and semi-detached houses for different countries (share of buildings). Data sources: US Census Bureau (2017), Eurostat (2016), and Statistics Japan (2013).

home charging in the Netherlands (Helmus et al., 2018; Hardman et al., 2018; NEA, 2019) indicates a low home parking availability for semi-detached houses. For China, no data was found, but its share of detached houses is expected to be low (e.g. Hardman et al., 2018; Nicholas and Hall, 2018).

In cities, the availability of home parking is lower than in (more) rural areas due to the higher population density (for Germany, cf. infas et al., 2018). For example, in Tokyo, the share of detached houses (30%) is well below the country average of ~55% (Statista, 2015). Accordingly, the share of urban population is another important influencing factor for private charging infrastructure. Yet, the urban share alone does not seem to be equally important in the different countries and regions. Rather, it should be interpreted in combination with housing types. In the Netherlands for example, the high share of urban population (92%, Table A1) might explain the low availability of home charging, whereas in California, the high share of detached houses (~60%, Table A1) does allow for a high availability of home parking (see above), despite its high share of urban population (95%, Table A1).

Finally, average yearly driving distances in the countries analyzed range between 7800 km for Japan and 17,700 km for the US (see Table A1). Accordingly, average daily driving distances are below 100 km and the necessary recharging times for these distances do not oppose to charging at home in any of these countries. However, as often stated in literature, average driving behavior is not very helpful to understand the market potential of PEV. Therefore, for SF4, we analyze the share of long-distance trips as an indicator of DC high power charging needs.

Altogether, the data supports the high availability of a home charging possibility for large parts of the population within most of the countries analyzed which, as broadly found in literature, is sufficient or even necessary for PEV adoption. However, due to the high share of detached houses in almost all countries, no correlation of the actual share of detached houses and the current PEV market size can be found.[1] But with regard to future prospects, different home charging availability might lead to different public charging infrastructure needs. Nevertheless, the high share of detached houses is promising for PEV adoption beyond current early adopters given that the installation of private charging infrastructure should be easy for large parts of the population in most of the countries.

In countries or regions with low home charging potential an effective substitute for home charging is necessary. In the Netherlands for example, the share of detached houses and thus the (potential) availability of private infrastructure is low which had to be compensated by public charging infrastructure. Similarly, in the highly populated Chinese megacities public charging infrastructure is necessary to compensate for missing private charging infrastructure, as discussed in SF3.

Workplace charging is another private charging option that might similarly be important for the future market development of electric vehicles since it might allow commuters to drive PEV even with no home charging infrastructure. While various studies highlight its importance, an assessment of workplace charging infrastructure stock is not possible at this point in time since it is built on private ground.

[1] A recent study by Münzel et al. (2019) on the effect of various financial incentives on PEV sales included the share of detached houses and the share of privately owned houses as additional controls but did not find clear evidence of a significant effect of the availability of home charging. However, no regression results were reported that contained both home ownership and public charging infrastructure as controls. This interesting question is, however, beyond the scope of the present paper and left for future research.

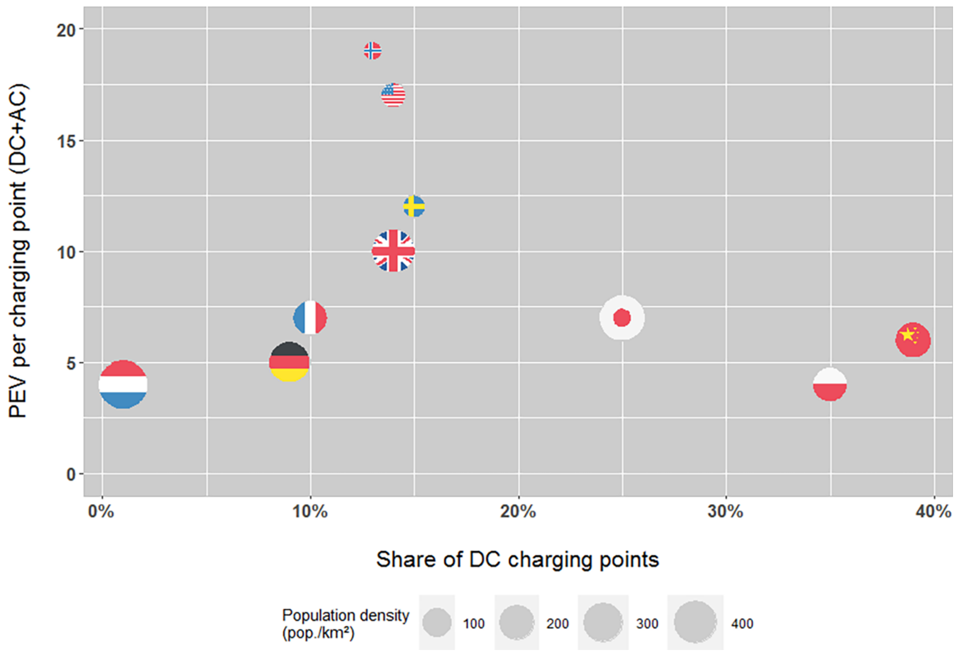

Fig. 3. Comparison of country DC charging point share and average PEV per charging point (DC + AC). Bubble size indicates population density. Data sources: IEA (2018) and UN (2017).

4.4. SF3: Public slow charging infrastructure is only needed as a substitute for home charging

In countries with low availability of private charging infrastructure (SF2), a large number of (potential) PEV users will be reliant on public charging infrastructure as an alternative. In principle, there are two options: (1) Public slow charging (AC) infrastructure is built where there is parking availability (parking lots, buildings or on-street-parking) nearby the home of PEV users for charging overnight (or close to work for charging during work time), or (2) public DC charging hubs are built in city centers and used similarly to today's fueling stations. The latter requires high grid connection power and high investment but will probably be profitable in the long-term (Gnann et al., 2018a). The collected data indicates that both options have been applied in different countries. However, all countries but Norway are still in an early, highly dynamic PEV market (see Table 4).

As an indicator for this stylized fact, we compare the average population density, the share of DC charging points and the VRI, measured in number of PEV per charging point (AC + DC) for the different countries (Fig. 3). The Netherlands has the highest average population density among the analyzed countries and, as discussed in the previous paragraph, a comparably low private charging infrastructure availability. In addition, it is also one of the more developed PEV markets in terms of relative PEV registration share and PEV stock per capita (Table 4). Accordingly, its low VRI – the lowest among all countries – indicates that a lot of public charging infrastructure has been built. The low DC charging share (see Fig. 1 and bubble size in Fig. 3) shows that the majority of the public charging infrastructure in the Netherlands is slow AC-charging. A large part of this infrastructure serves as a substitute for home charging (cf. Helmus et al., 2018). In contrast, Japan and especially China have a high share of DC public charging infrastructure, which is probably used for charging in highly populated areas as substitute to nonexistent home charging. Here, fast charging infrastructure might be the favorable option, since it can serve more vehicles and since also parking spaces (especially dedicated for overnight charging) are scarce. As discussed before, China may have a comparably low average population density, but it has several highly populated so-called megacities. Finally, Norway has the highest VRI and its DC charging point share is in the medium range. Since Norway is also the most developed PEV market, the data underlines that a high VRI is not an appropriate metric to indicate further charging infrastructure expansion needs, at least not without additional data on market maturity. For Sweden, the interpretation applies analogously.

Finally, there was no further information on public slow charging infrastructure (such as sites), so we could not assess the importance of POI charging. However, there might be some indications. In the Netherlands, Helmus et al. (2018) found demand driven charging points to perform better in immature markets than strategic charging points. Since in all countries, except probably Norway, even the relatively more developed PEV markets are still immature as compared to the total car market, this finding might underline the current importance of public charging infrastructure as substitute for home charging in the Netherlands. In addition, in some countries where home charging is broadly available, public slow charging infrastructure is rarely used (Gnann et al., 2018c; EVProject, 2013) and public fast charging infrastructure is found to have higher impacts (Levinson and West, 2018).

There are however some indications that availability and awareness of public charging infrastructure can have a positive effect on the willingness to purchase or lease a BEV (Carley et al., 2019) especially for groups that are not the typical early adopters (Globisch et al., 2019).

Due to the early PEV market in combination with a high availability of home charging in most countries, there is no clear evidence of the role of public slow charging infrastructure. However, the strikingly high percentage of public slow charging infrastructure (compared to public fast) in combination with the low availability of home charging possibilities in the Netherlands backs SF3, especially when compared to the other countries that are more homogeneous in this regard. If public charging infrastructure is built for commuters, it similarly serves as substitute for missing private infrastructure as discussed for home charging. Therefore, we regard the hypothesis as valid nevertheless.

4.5. SF4: DC high power charging infrastructure is mainly needed for BEV long-distance trips

While DC charging infrastructure might also serve as substitute for private charging in cities (see SF3), DC charging is especially important for long-distance driving, since there is no alternative for pure battery electric vehicles. One option to differentiate both DC charging use cases would be charging power: While for long-distance trips, short charging times are crucial, DC charging within cities may be of significantly lower charging power (cf. Funke et al., 2019). However, current data on DC charging points rarely differentiate charging power levels and thus a distinction between the two very different use cases for fast charging is not possible to date.

Accordingly, the share of DC charging points itself is only to a limited extent suitable to investigate SF4. For this reason, we analyze DC charging infrastructure in general and its theoretical coverage of highways (based on country-specific road network data). We focus on highways, since long-distance trips predominantly take place on highways (Zhang et al., 2015). With regard to future needs, we analyze the share of long-distance trips within the different countries as an indicator of fast charging needs along highways (cf. Gnann et al., 2018).

The availability of DC charging infrastructure is already high for most countries under analysis. The average highway distance between DC charging points is below 20 [km] for all countries yet with a wide variation. While Norway, the most developed market in terms of PEV share in sales and stock, has the lowest ratio (0.4 highway-km per charging point), the US and Poland have the highest (17 and 15, respectively). For the US, the large country area and the large variety between individual states might explain this. Please note that these ratios (see also Table 6) are of theoretical nature. The actual coverage of DC charging infrastructure at highways is lower since on the one hand, not all charging points are installed along highways and since on the other hand one charging station often consists of multiple charging points. Accordingly, under the assumption of four charging points per site, the ratio of highway kilometers to charging sites would be four times higher as shown in Table 6, while the average radius around a charging site would be twice as wide.

With regard to future DC charging infrastructure needs (along highways), some country specific differences are worth mentioning. First, highways cover a higher share of the countries surface area in denser populated countries. The coverage (length of highway network [km] to country surface area [km^2]) ranges from 0.2% in Norway to up to 3.6% in Germany (Table 6). Accordingly, in denser populated countries, charging stations along highways would also cover the country better. Second, the countries differ also with regard to gasoline station coverage. While in Japan, Norway, and Poland, the average highway distance between gasoline stations is as low as 0.3, this ratio is four times as high in China. These country-specific differences must be taken into account. The ratio of charging points per gasoline stations might be a suitable parameter to account for these differences (see Table 6) although the high usage of DC charging infrastructure in cities (as e.g. in China) might dilute this parameter to some extent.

Finally, no correlation between the share of BEV and the share of DC charging points is discernible (c.f. Table 4 and Fig. 1). However, the high share of long-distance trips in Sweden, but also Norway, implies a relatively higher need for highway DC charging infrastructure than in the other countries. Data on long-distance trips was only available for half of the countries.

Altogether, the data illustrates the high efforts made by almost all countries analyzed to build up public DC charging infrastructure - although the countries have different expansion levels. Since especially data on DC charging power was not available, it is difficult to assess the importance of DC charging for long-distance trips compared to other use cases. In combination with SF3 however, we can conclude that in some countries DC charging might also be necessary to compensate for missing private charging infrastructure (such as China), but that especially high-power charging will be needed for long-distance trips due to the absence of other alternatives. Also, similarly as for slow public charging awareness of a DC charging net might increase the willingness to purchase a BEV. Overall, the data situation does not permit stronger conclusions.

Table 6
DC charging infrastructure (Year 2017), highway and long distance travel data. Data sources: IEA (2018); EAFO (2017); UK (2017); gddkia (2017); FHA (2017); Statista (2017b); MILT (2017); WPR (2019); Christensen et al. (2014); Collia et al. (2003); Dargay and Clark (2012).

Parameter	China	US	France	Germany	Japan	Netherlands	Norway	Poland	Sweden	UK	World
Highway network to country area [km/km^2]	0.014	0.012	0.021	0.036	0.027	0.074	0.002	0.007	0.004	0.015	n/a
Highway km per DC-CP	2	17	7	6	1	7	0.4	15	3	1	n/a
Average radius [km] around a DC-CP	6	22	11	7	4	5	9	26	15	4	20
Highway-km per gasoline station	1.2	0.6	1.0	0.9	0.3	0.7	0.3	0.3	0.6	0.4	n/a
DC-CP per gasoline station	0.76	0.04	0.14	0.14	0.18	0.11	0.68	0.02	0.21	0.74	n/a
Share of long-distance travel on daily mileage [%]	n/a	n/a	29%	27%	n/a	31%	35%	n/a	43%	26%	n/a

4.6. Summary of country comparison

In the previous paragraphs, the focus of our comparison was on the single parameters and the differences between countries. In order to be able to classify the different framework conditions in combination, we summarize our results in exemplary descriptions of the framework conditions in individual selected countries.

In the Netherlands, the low availability of detached houses is noticeable. As described above, the availability of detached houses is an indicator for the availability of home charging, especially in the medium- to long-term. Accordingly, we find the highest share of AC slow charging infrastructure (among the countries analyzed) in the Netherlands. Since the Netherlands also have the lowest number of PEV per charging point, a dense network of public slow charging infrastructure was built not only for POI charging but also as important alternative to home charging infrastructure in the Netherlands.

The size of public DC fast charging infrastructure in the Netherlands, in terms of the ratio of pure battery electric vehicles to DC fast charging infrastructure, is in the middle range of the countries analyzed just as much as the share of long-distance trips (30%). This suggests that DC fast charging infrastructure in the Netherlands serves indeed for full electric long distance driving as a dense fast charging network along the highways shows (which for the most part already existed in 2017, namely 63 stations out of today's 80, but with lower charging power (Fastned, 2018)). However, the total number of DC fast chargers and the share of DC fast chargers among all public chargers is small (cf. Fig. 3). This can be attributed to a number of reasons, special for the Netherlands. First, the Dutch PEV fleet has been dominated by PHEV for several years which can perform long-distance trips without recharging during the trip. Second, bigger cities in the Netherlands like Amsterdam have installed slow chargers on public parking spaces for PEV owners without garages, such that no additional DC fast charger demand arose here. Third, the limited area of the Netherlands implies that long-distance car travel, e.g. for vacation, is mostly outside the Netherlands, e.g. to Germany, the Alps or the Mediterranean.

In the other countries, home charging is very important and will probably remain so as indicated by the high availability of detached houses in these countries. Accordingly, public charging infrastructure in these countries will be important in densely populated (metropolitan) areas with low availability of home charging infrastructure. Outside these metropolitan areas, where the likelihood of home charging availability is high, public charging infrastructure is in general less important as substitute to home charging.

The US has the highest availability of detached houses (and garages) which is also reflected by the high share of home charging availability among current PEV users in the US. The ratio of PEV to public charging points (AC + DC charging points) is relatively high. However, the share of DC fast charging infrastructure (14%) as well as the ratio of DC charging points per gasoline stations is relatively low in the US, which suggests that a dense public charging infrastructure in the US does not exist yet. One reason might be that the electric market is focused to some PEV hotspots within the US. Accordingly, Nicholas et al. (2019) find that charging infrastructure deployment activities are uneven across the country.

Germany has the second lowest share of detached houses (about 25%), but the availability of parking spaces on private property is nevertheless high (75% on average), especially in suburban areas (Infas et al., 2018). Corresponding to this fact, early adopters of PEV in Germany typically live in suburban areas (Plötz et al., 2014). Although approximately half of all PEV in Germany (in 2017) are battery electric (BEV), the share of DC charging is relatively low in Germany while the ratio of PEV to all public charging points (AC + DC charging points) is on international average. Indicators for a lower DC charging infrastructure need in Germany could be both the below average share of long-distance trips and the remarkably above average ratio of conventional cars (ICEV) to the number of gasoline stations compared to other countries.

In China, most of the PEV are battery electric (BEV). A very low ratio of PEV to public charging points and a high amount of DC charging infrastructure show the high ambition of political actors in China to support PEV market diffusion by building public charging infrastructure at large scale. Especially the deployment of DC fast charging infrastructure seems to be far advanced (e.g. when compared to the number of gasoline stations) since these might be partly used as charging hubs in megacities where home charging might not be broadly available.

Finally, we turn to Norway, the market with highest PEV diffusion. Norway has a high share of detached houses and a high share of pure battery electric vehicles (BEV). Accordingly, the deployment of DC fast charging is also far advanced compared to the gasoline infrastructure. However, the share of DC public charging is in the middle range of the countries and the ratio of PEV to all public charging points (AC + DC) is also one of the highest. Altogether, these findings underline the fact that the vehicle-to-refueling-index (VRI, here: the number of PEV per charging point) as a single measure can only be used to a very limited extent for the comparison of charging infrastructure deployment, especially if no further background information is given.

5. Discussion

In our analysis, we focused on the identification and presentation of parameters that are relevant to discuss public charging infrastructure needs in an international context. In that sense, our study gives impulses for future research to better transfer lessons learned from charging infrastructure deployment on regional or national level to other countries. For example, our parameter set might be used to monitor the development of charging infrastructure and its influence on PEV market within the upcoming years. Or, the data gathered in this study might be used for the comparison of different countries within existing PEV market diffusion models. In addition, the need for public chargers will not only differ between countries but also between regions within larger countries.

Our study comes with limitations that need to be addressed in the future. First, we mainly focus on major markets of PEV since they comprise almost all PEV sold worldwide (IEA, 2018). However, we derive our stylized facts based on current literature which mainly analyze PEV adoption in the US and Europe. China is a highly dynamic PEV market with specific characteristics that might be underrepresented in the choice of the stylized facts - such as the importance of megacities. Further research might analyze these countries more deeply as well as countries that will impact future development, but are not relevant today, such as e.g. India. In addition, we are still in an early PEV market phase in almost all countries, which makes interpretation of current status of charging infrastructure deployment and its importance for PEV diffusion problematic. Accordingly, the focus of our study is on underlying parameters and data availability. However, some data was not available or only on aggregated level. For example, we used the share of detached houses as indicator of home parking availability. Yet, Germany has a comparatively low share of detached houses but a high availability of garages. Similarly, a distinction between public fast charging within cities and high-power charging for long-distance trips is not possible on the current data situation, mainly due to missing charging power data. Thus, in the future, these two fast charging options should be shown separately, e.g. in the IEA's Global Energy Outlook (IEA, 2018). Altogether, our research provides a broad perspective of different framework conditions of public charging infrastructure in an international context. To the authors' best knowledge, this is one of the first study of its kind and provides insights for policymaking and future research.

Finally, for a global success of charging infrastructure, interoperability and reliability of use are key. Here, these aspects are not analyzed, since they are equally important for all countries. In addition, technical aspects of charging infrastructure, such as charging modes, charging standards or PEV grid integration, are beyond the scope of this paper and they are broadly addressed in the existing literature. For details on these aspects see, e.g., Hardman et al. (2018).

Altogether, our study shows that fast charging needs may vary under different circumstances. These aspects have to be considered in future modeling of charging infrastructure needs. While currently, various models exist to determine specific types of charging infrastructure, such as fast charging infrastructure along highways, further research is necessary to better understand the interaction effects between the different charging infrastructure types (home, work, public). For example, a dense fast charging network might serve for long distance trips as well as substitute for home charging if usage is convenient enough. Thus, beyond techno-economic analyses on charging infrastructure needs, especially social research is necessary to better understand charging infrastructure user needs beyond early adopters. Finally, while national charging infrastructure planning can and should give guidelines and target corridors for charging infrastructure set-up, planning and placing of charging infrastructure, except for fast charging infrastructure along highways, will happen on local scale due to local specifics. Our research supports future research by revealing important influencing factors and thus helps making more country-specific and more accurate estimates on national charging infrastructure needs.

6. Summary and conclusions

In this paper, we analyze the role of framework conditions on charging infrastructure needs for different countries. To this aim, we perform a literature review with the focus on deducing stylized facts that describe the influence of framework conditions on public charging infrastructure needs valid across studies, but focused on specific countries. We identify four stylized facts (SF) on home, public slow and public fast charging as well as the corresponding key parameters. Second, we compare these parameters for several countries to illustrate how these countries differ with regard to these framework conditions. For the illustration, we use two perspectives: a parameter specific comparison where we highlight the differences between countries (Section 4) and an analysis of the framework conditions for specific countries as represented by the set of parameters. Thus, this paper contributes to the definition of good conditions for charging infrastructure set-up that are valid or interpretable in an international context.

We conclude the following based on the aforementioned two perspectives.

1. Home charging is currently the most important charging option in most countries and will remain so in many countries with high home charging opportunity for users beyond current early adopters. In countries, or regions with low potential home charging availability, public charging infrastructure will be important as substitute.
2. Thus, public slow charging infrastructure as *conditio sine qua non* for PEV use will remain important mainly in some metropolitan areas, but not on national level - with few exceptions. For commuters, especially for those with no home charging option, a regular workplace charging is an important option.
3. The role of DC high power charging infrastructure will differ by country due to differences in long driving shares and highway coverage. However, the data does not support strong conclusions, not least, because DC charging infrastructure might be used as alternative to home charging (as for example is probable in China).[2]
4. Countries differ with regard to their charging infrastructure framework conditions. Accordingly, there is no optimal share of PEV per charging point (VRI) for every country and charging type. Therefore, charging infrastructure deployment in different countries should be discussed in a larger context rather than being based on the VRI as sole measure.

Altogether, our findings show that charging infrastructure needs for a specific country might be only generalizable when the effects of framework conditions are reflected.

[2] Some existing studies show that DC fast charging occurs closer to home than required (Hardman et al., 2018). However, this observation can be biased by many initial DC fast chargers that were free of cost. There is evidence that users charge more at DC chargers if it is free than required to complete their driving (Hardman et al., 2018).

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Appendix A. Supplementary material

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